Interannual to multi-decadal forcing of mesoscale eddy kinetic energy in the subtropical southern Indian Ocean

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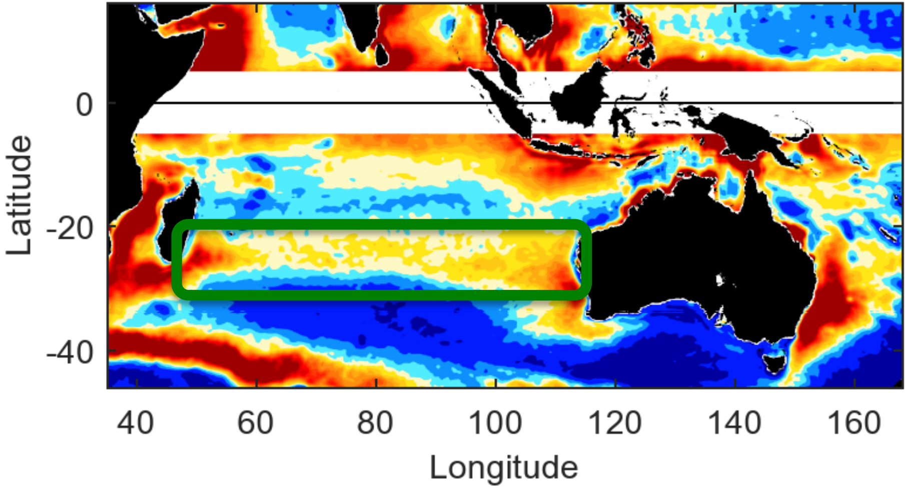


Image: Time-mean surface eddy kinetic energy, from SSALTO/DUACS altimetry product

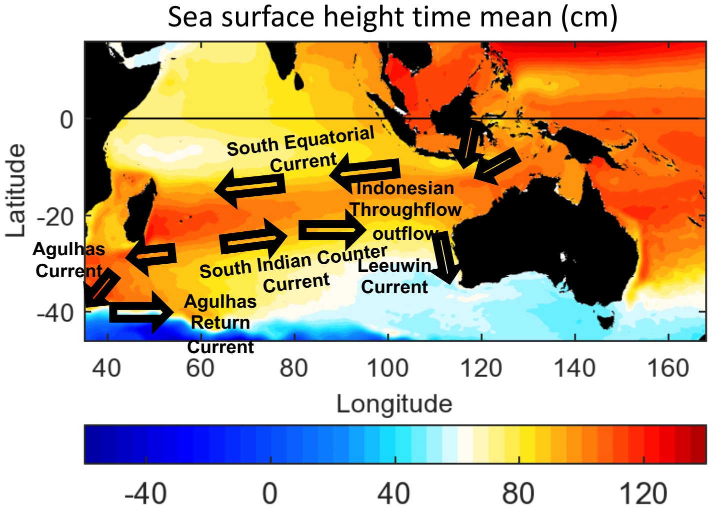
APL, University of Washington seminar
4 October 2018

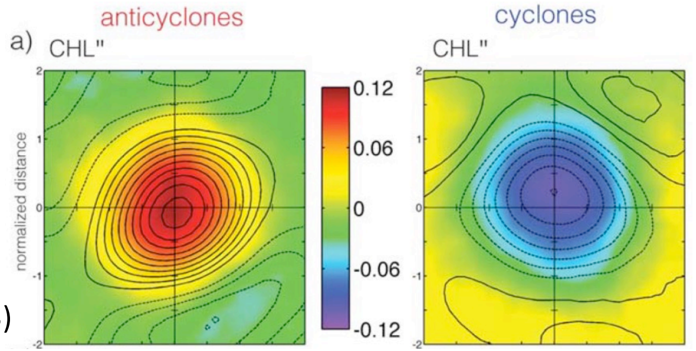
Jet Propulsion Laboratory
California Institute of Technology

Why study eddies in the subtropical southern Indian Ocean (SSIO)?

SSIO eddies are not as energetic as eddies in some other areas, however they…

- Are located at the intersection of numerous currents, including an unusual poleward-flowing eastern boundary current (Leeuwin Current)
- Are important for heat transport of the IO shallow overturning circulation (Lee and Marotzke 1998, Schott et al. 2002, Lee 2004), and may interact with the atmospheric boundary layer
- Have significant impacts on chlorophyll anomalies in the region (Gaube et al. 2013, Gaube et al. 2014)

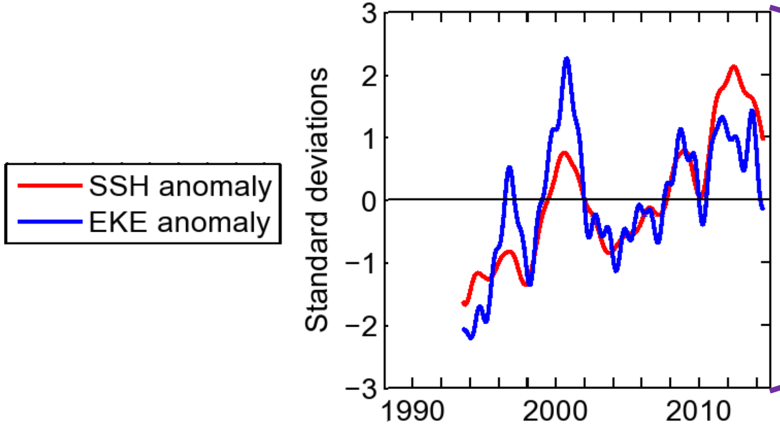




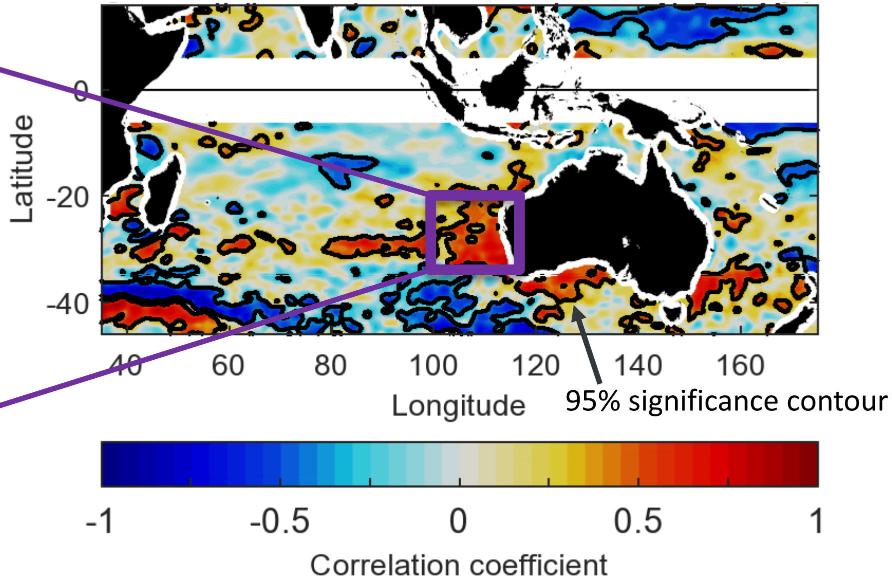
Composite chlorophyll anomalies of SSIO eddies (Gaube et al. 2013)

SSIO sea surface height (SSH) and eddy kinetic energy (EKE) variability

SSH and EKE anomalies from altimetry, averaged west of Australia



SSH-EKE anomaly correlation after detrending, 0 lag. Filtered for interannual/decadal (ID) timescales.



- **Why are SSH and EKE anomalies correlated in the eastern SSIO (Leeuwin Current region)?**

Research questions

- **Which mechanism(s) explain the close relationship between SSH and EKE on interannual/decadal timescales in parts of the SSIO?**

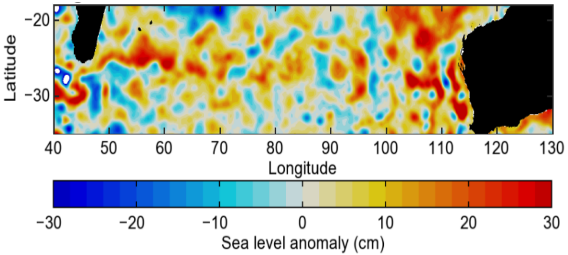
…with possible implications for multi-decadal trends in EKE and SSH

- **Which climate and/or interior ocean forcings control the interannual and decadal variability of EKE in the SSIO?**

…with implications for heat/tracer transport variability/predictability, and ecosystem behavior

Separation of oceanic motions by spatial scales

In order to focus on dynamics at mesoscales (tens of km to ~200 km)
- Low-pass filter SSH (or SLA, i.e., SSH anomaly) in both longitude and latitude
- Use 6° wavelengths (~670 km) as the cutoff threshold, based on eddy scales in Chelton et al. (2011)



SSALTO/DUACS SLA snapshot 2011 Jul 02

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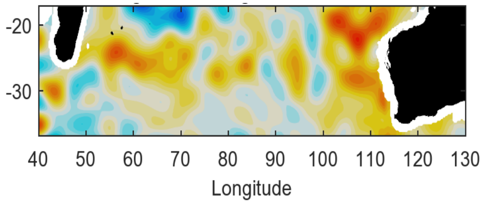
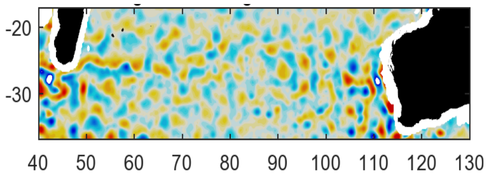


SLA_{lp}

+



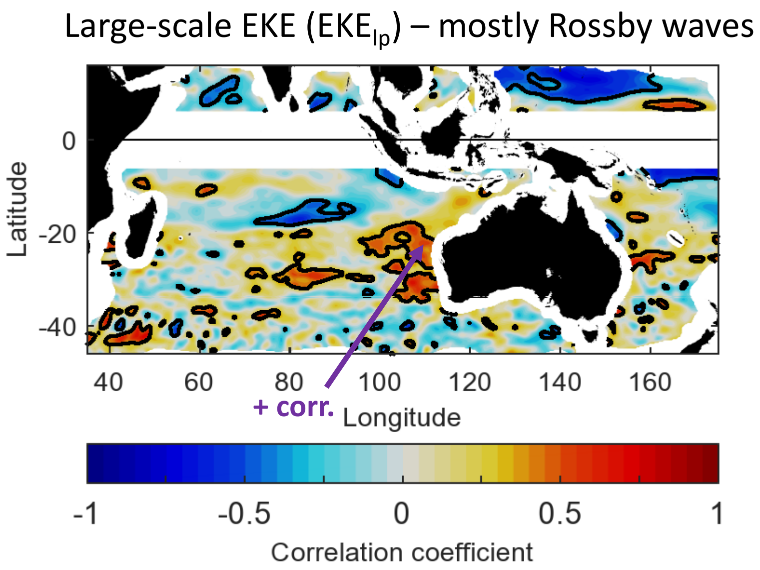
SLA_{meso}

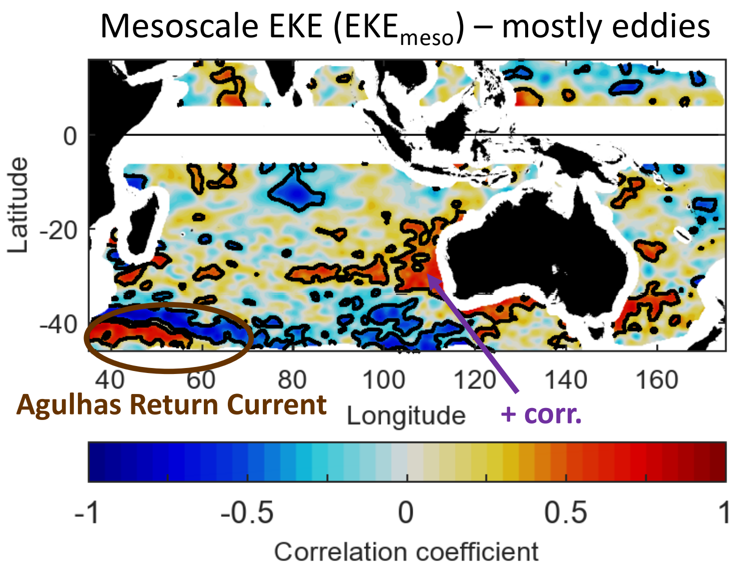
- The low-passed field represents larger-scale motions
- Residual represents mesoscale motions (such as eddies)
- **EKE can be computed from each individual field, e.g.,**

$$\mathrm{EKE}_{\mathrm{meso}} = \frac{1}{2}\left\|\hat{\mathbf{k}}\times\frac{g}{f}\nabla(\mathrm{SLA}_{\mathrm{meso}})\right\|^2$$

Correlation between SSH and EKE at interannual/decadal timescales

Zero-lag ID correlation of unfiltered SSH and





- Robust positive correlation between SSH and EKE associated with both large scales and mesoscales
- SSH relationship with **mesoscale** EKE gets more robust at higher latitudes, where eddies also account for much more energy than planetary waves

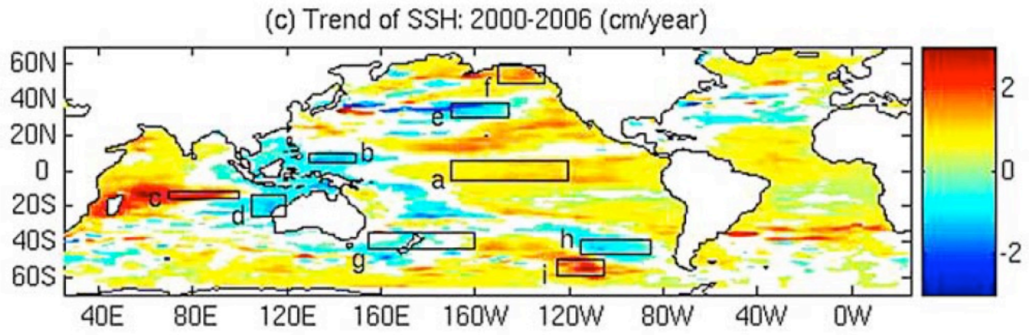
Why care about the relationship between SSH and EKE?

- Large-scale changes in sea level indicate shifts in ocean currents and/or planetary waves that may drive changes in conditions for eddy generation

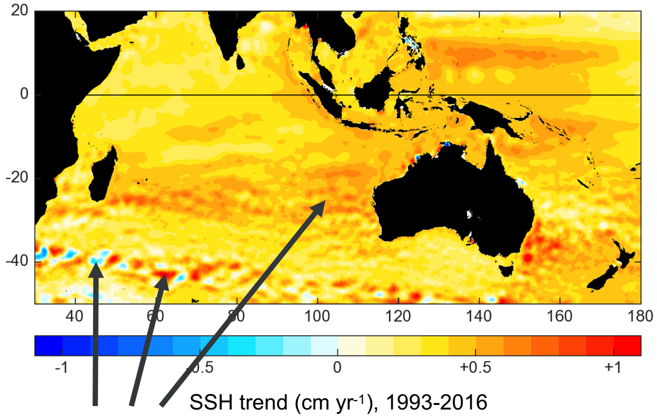
Sea level → dynamics → eddies

- On the other hand, mesoscale patterns in sea level variability and/or trend imply that mesoscale phenomena (eddies) are influencing sea level

Eddies → sea level



Lee and McPhaden (2008)



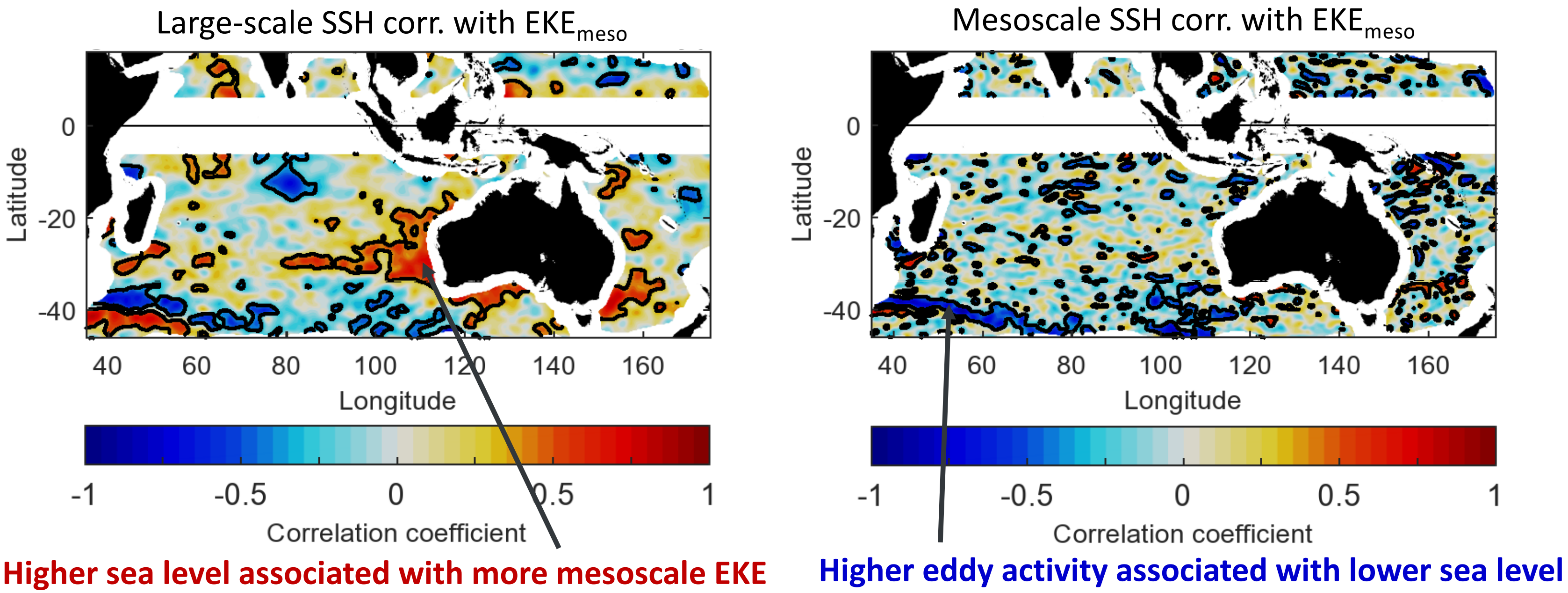
Mesoscale features in SSH trend

Scale-dependence of SSH-EKE relationship

- In the subtropical eddy band, the SSH-EKE relationship is associated almost entirely with large-scale SSH variability

Sea level → dynamics → eddies

- This contrasts with the Agulhas Return Current/ACC region to the south, where eddies contribute to sea level variability



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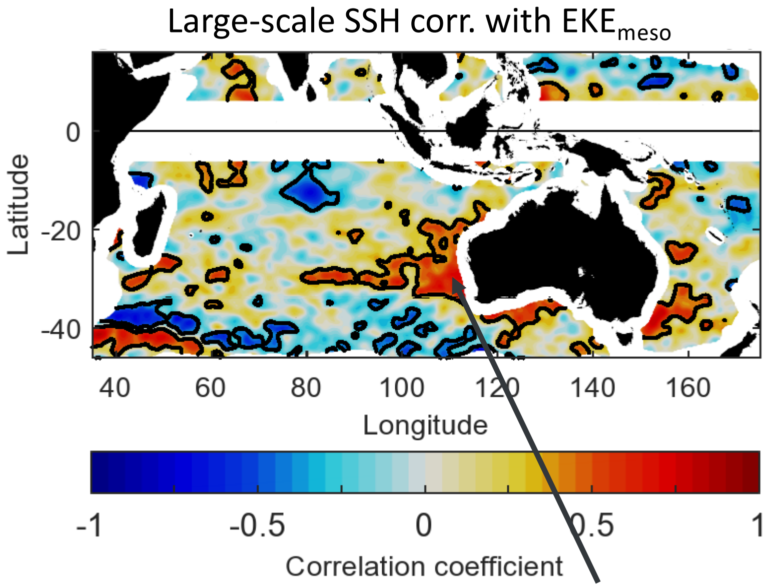
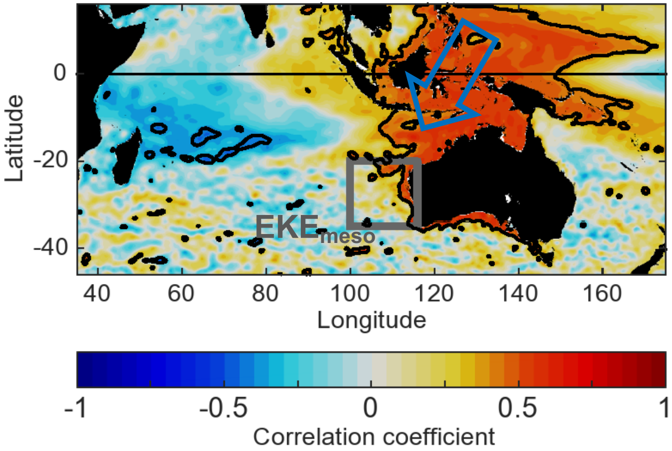


Higher sea level associated with more mesoscale EKE

Why?

Hypothesis: Pacific variability forces both SSH and mesoscale EKE variations in eastern SSIO

Correlation of SSH leading box-averaged EKE_{meso}
6 month lead time

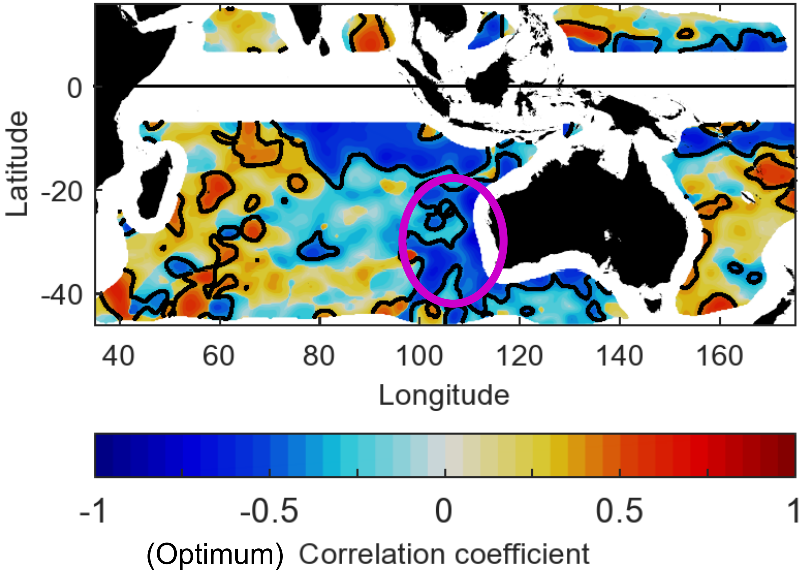


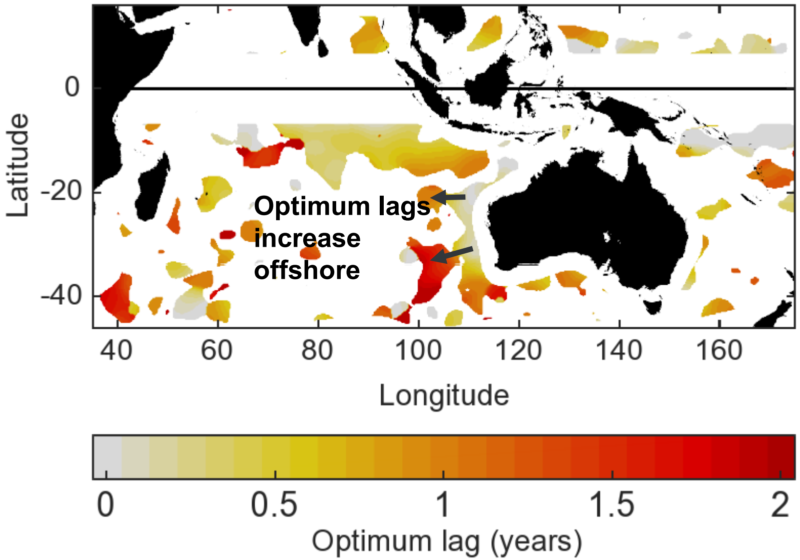
NW tropical Pacific SSH leads EKE_{meso} W of Australia by ~6 months

- Correlation implies that Pacific dynamics are an important influence on SSIO eddy activity
- Any connection with the tropical Pacific also implies a connection with ENSO…

Optimum correlations of Niño3.4 index leading mesoscale EKE

- Here we carry out an "optimum correlation" analysis…correlate the Niño3.4 index with the time variation in mesoscale EKE around the region at varying lags
  - Plot the **maximum magnitude** correlation coefficient at any lag in a 0-2 year range

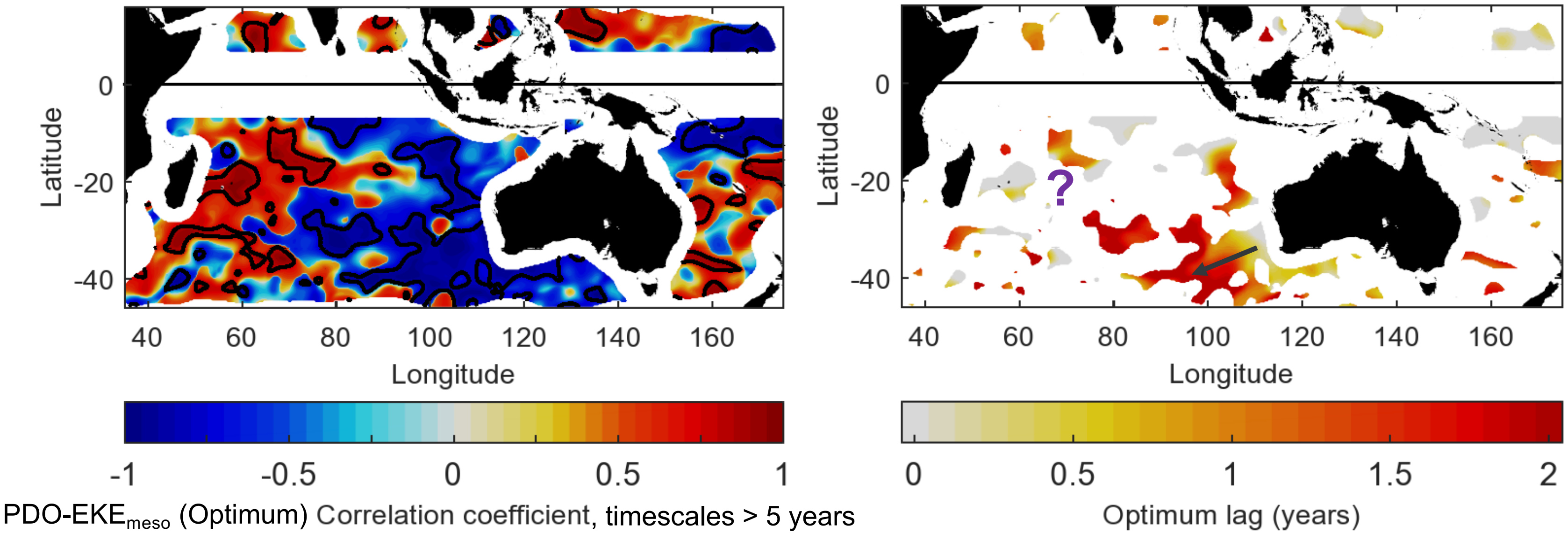




- La Niña (negative Niño3.4) produces higher sea level in W tropical Pacific → stronger Leeuwin Current → **more eddy activity**

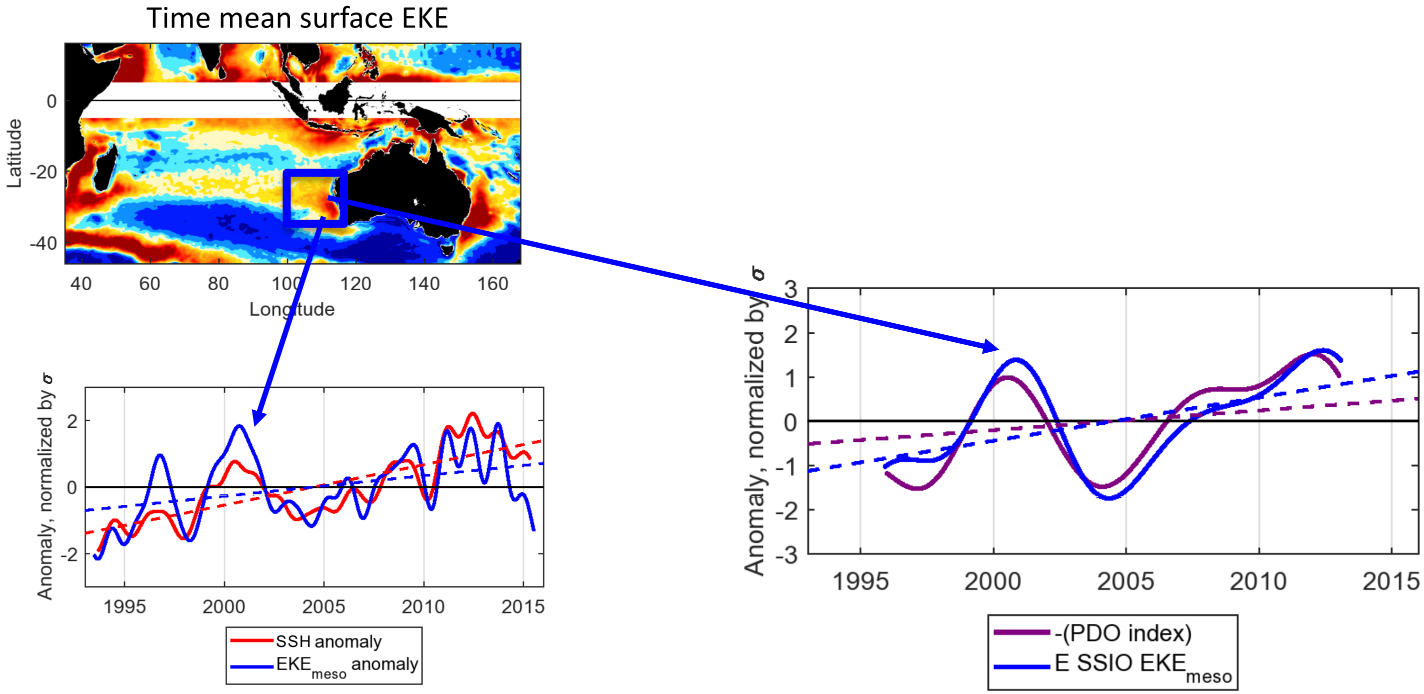
Decadal variability (PDO) and mesoscale EKE in the SSIO

- If ENSO has such a robust influence on eddy activity west of Australia, does the dominant mode of decadal variability in the Pacific (PDO) have a similar effect?



- Pacific forcing has a more robust and far-reaching effect on mesoscale EKE at decadal timescales than interannual timescales!
- Though this still doesn't explain mesoscale EKE variability in the **central and western SSIO**

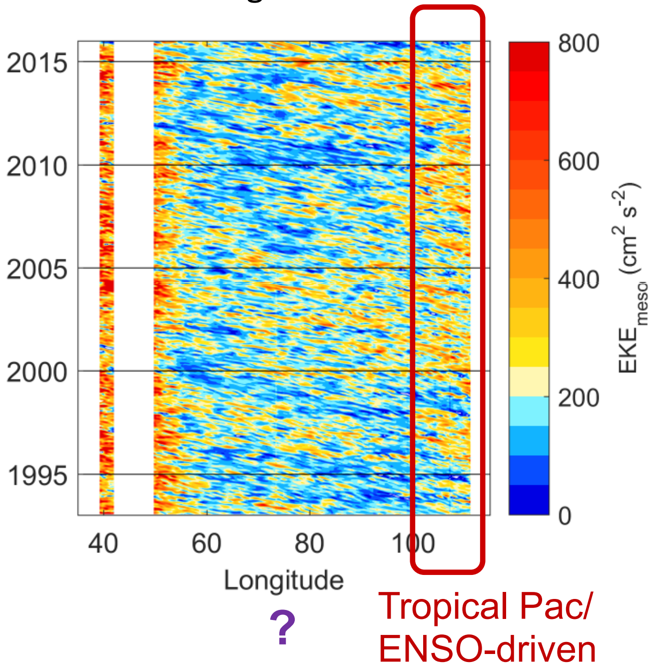
Decadal variability (PDO) and mesoscale EKE in the SSIO



- The decadal part of the **SSH** and **mesoscale EKE variations** in the eastern SSIO are **very** well explained by variations in the **PDO index**

- What drives eddy variability away from the Leeuwin Current (central & western SSIO), in the absence of large-scale climate forcing?

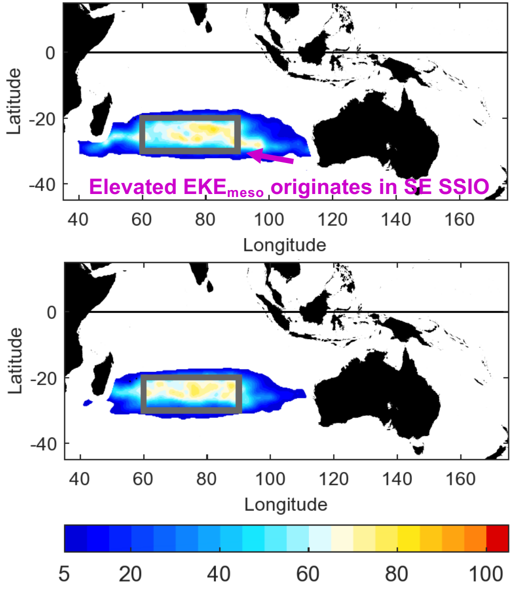
Hovmöller diagram of mesoscale EKE, averaged 25°-20° S



- Using eddy trajectory dataset (developed by Chelton et al., now distributed by AVISO), quantify EKE$_{meso}$ associated with eddy tracks passing through the central/western SSIO

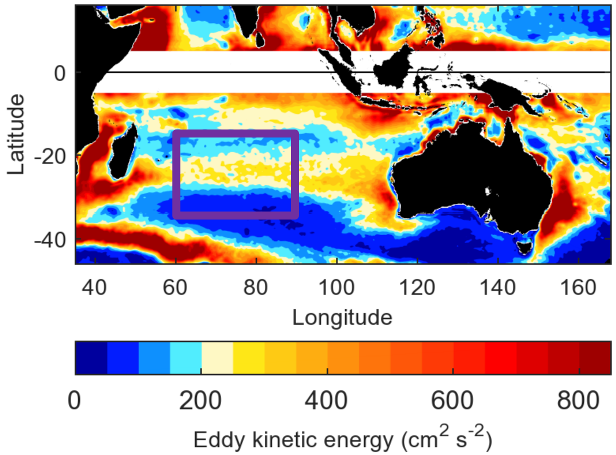
Anticyclonic EKE$_{meso}$ (cm^2 s^{-2})

Cyclonic EKE$_{meso}$ (cm^2 s^{-2})

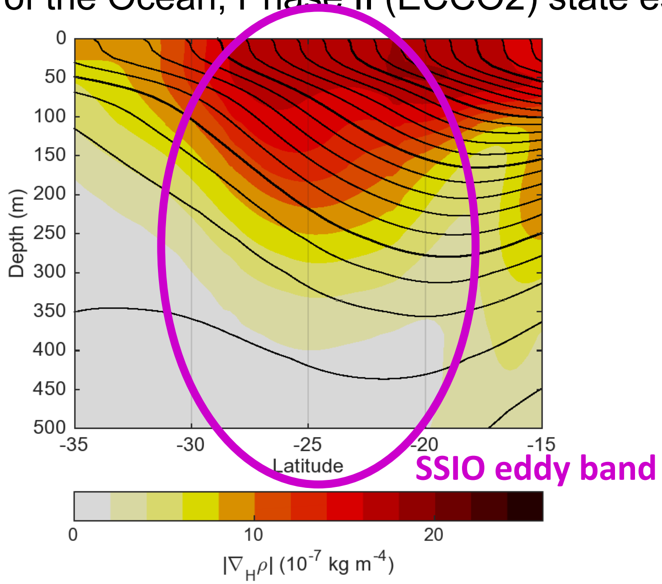


The impact of density and potential vorticity gradients

- Available potential energy (APE) is a function of the local density variance at a given depth, related to the lateral density gradient $\nabla_H \rho$, as well as vertical shear of horizontal velocity $\partial u/\partial z$, $\partial v/\partial z$
- We use the Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2) state estimate to examine these gradients



Time mean surface EKE from altimetry



Magnitude of lateral density gradient from ECCO2
Time mean and zonally-averaged, central/western SSIO

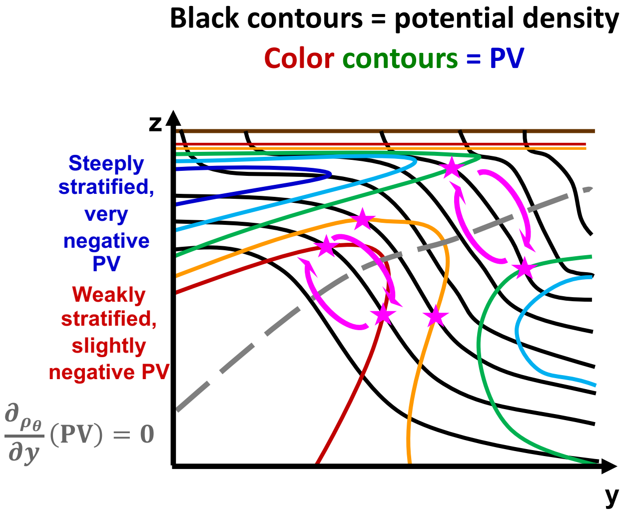
- But just because APE is present doesn't mean baroclinic instability follows
  - Nor do APE variations necessarily drive EKE variations

The impact of density and potential vorticity gradients

- Charney and Stern (1962) considered baroclinic instability (in the atmosphere) from the perspective of potential vorticity (PV) gradients along isopycnals

negligible in SSIO

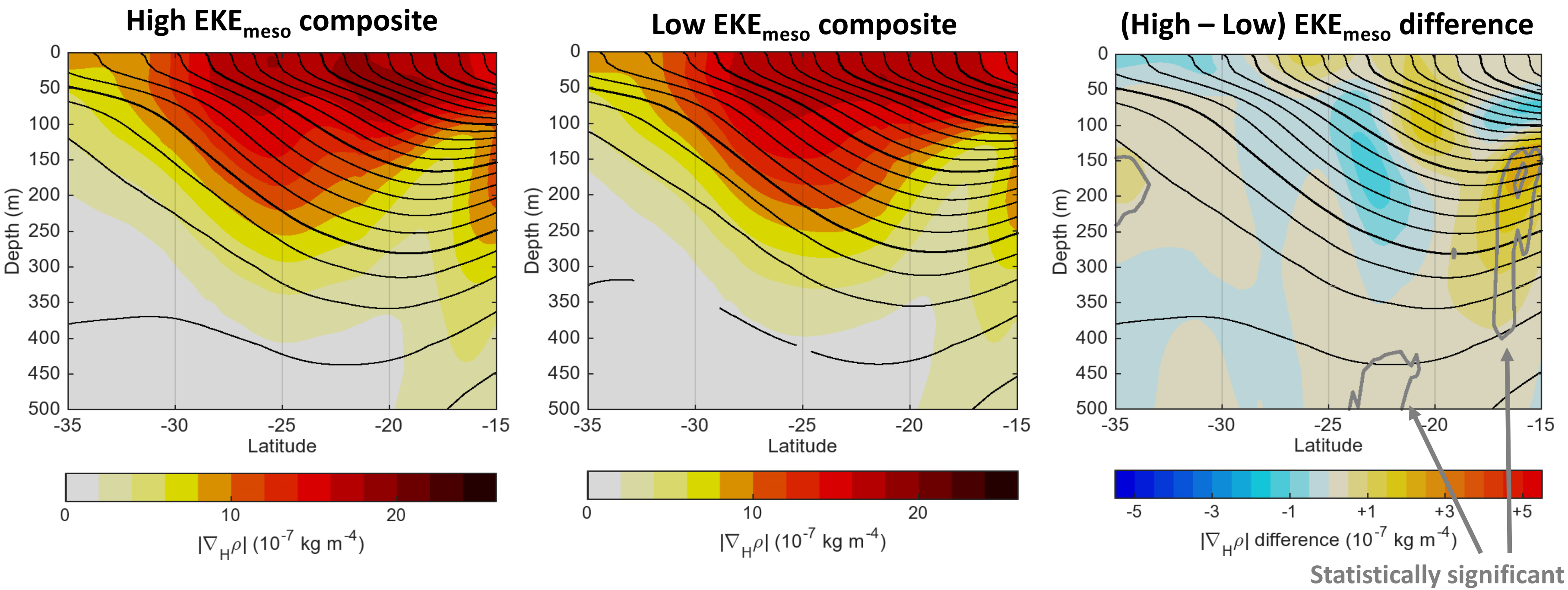
$$PV = \underbrace{(f + \cancel{\zeta})}_{\substack{\text{Pos. in NH} \\ \text{Neg. in SH}}} \underbrace{\left(-\frac{\partial \rho}{\partial z}\right)}_{\text{Positive}}$$



- Zero crossing in the PV gradient along a sloping isopycnal implies the potential for parcels at different depths but similar PV to be exchanged
  → potential release of APE and growth of baroclinic instability

The impact of density and potential vorticity gradients

- **Lateral density gradients** help explain the existence of the SSIO eddy band…do they help explain its temporal variability?

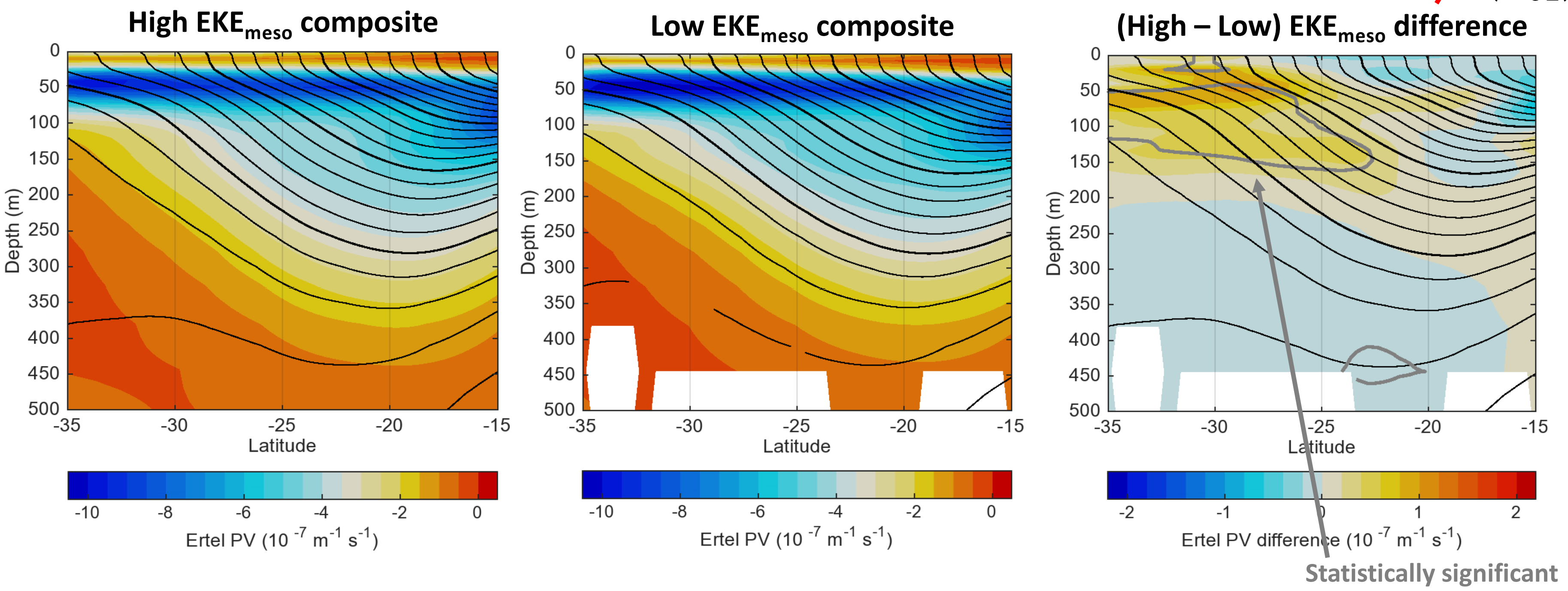


- Slight differences between composites of high vs. low eddy activity are generally **not statistically significant**

The impact of density and potential vorticity gradients

- What about **potential vorticity**, whose variability is driven by changes in stratification/thickness?

$$PV = (f + \cancel{\zeta})\left(-\frac{\partial \rho}{\partial z}\right)$$

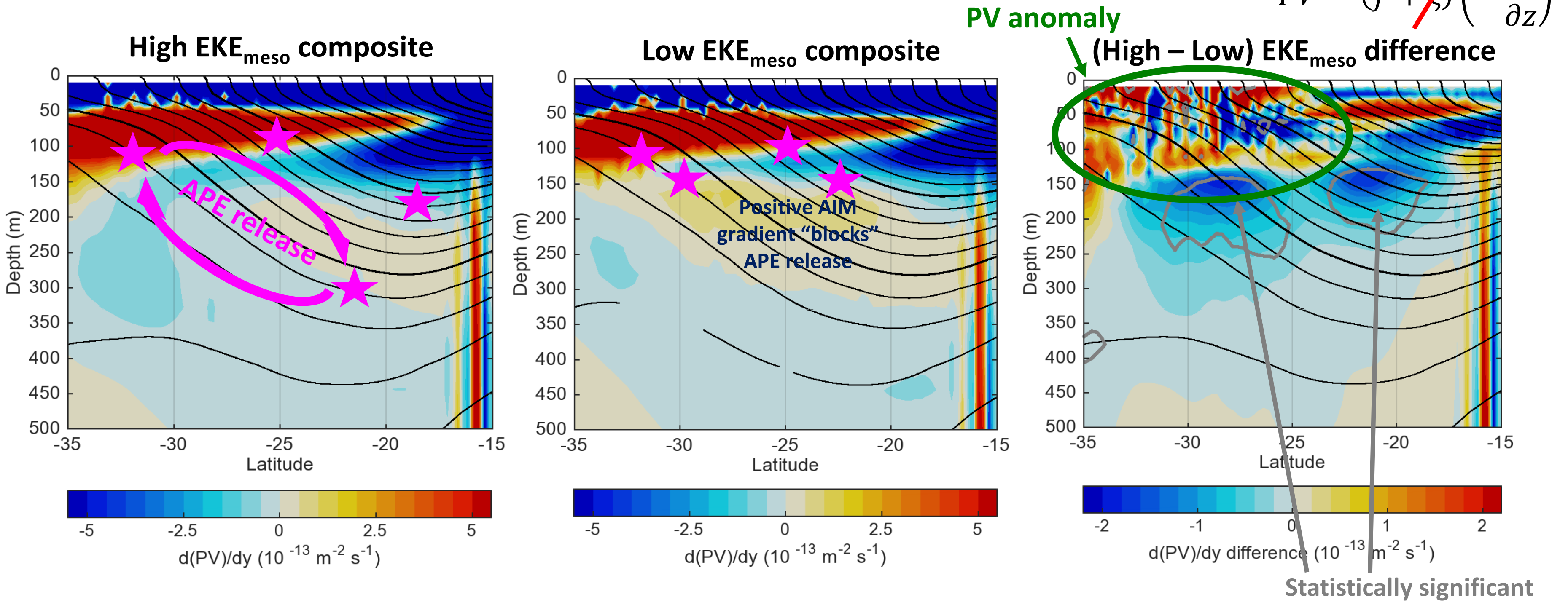


- There is a significant difference in PV between high and low eddy states
  - i.e., higher PV in the southern part of the eddy band (50-150 m depth) → more eddy activity

The impact of density and potential vorticity gradients

- Now consider the **along-isopycnal meridional (AIM) gradient of potential vorticity**

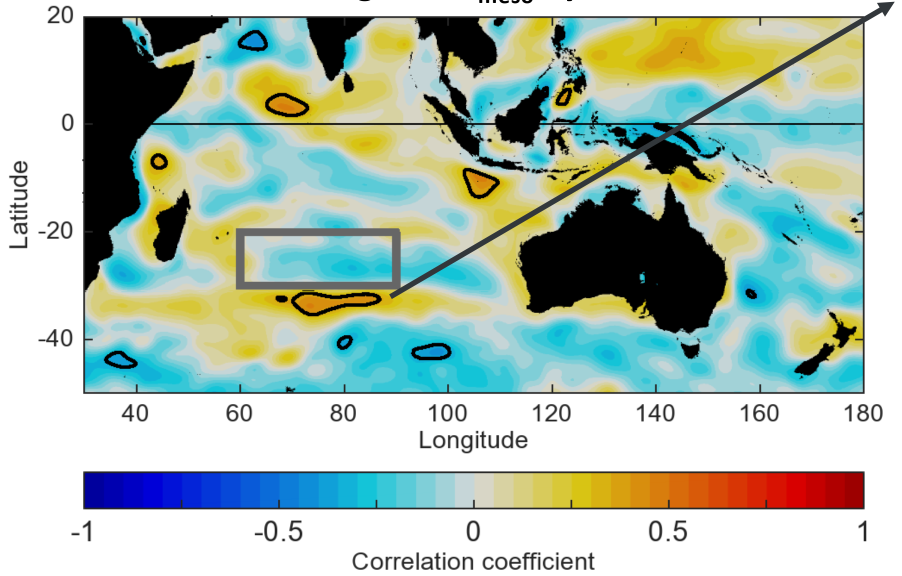
$$PV = (f + \cancel{\zeta})\left(-\frac{\partial \rho}{\partial z}\right)$$



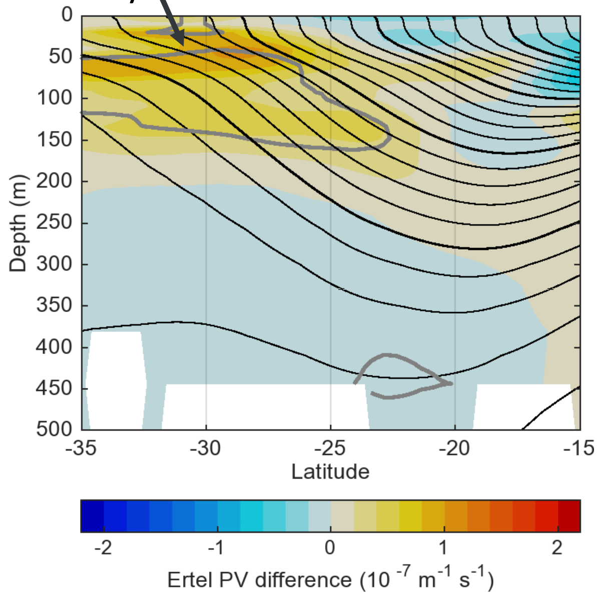
- Negative AIM gradient anomalies associated with higher eddy activity
  - Likely driven by the positive PV anomaly on the southern side of the eddy band

If the PV anomaly influences mesoscale EKE levels, how is it forced?

Correlation of wind stress curl (from CCMP), leading box-averaged EKE_{meso} by 6 months

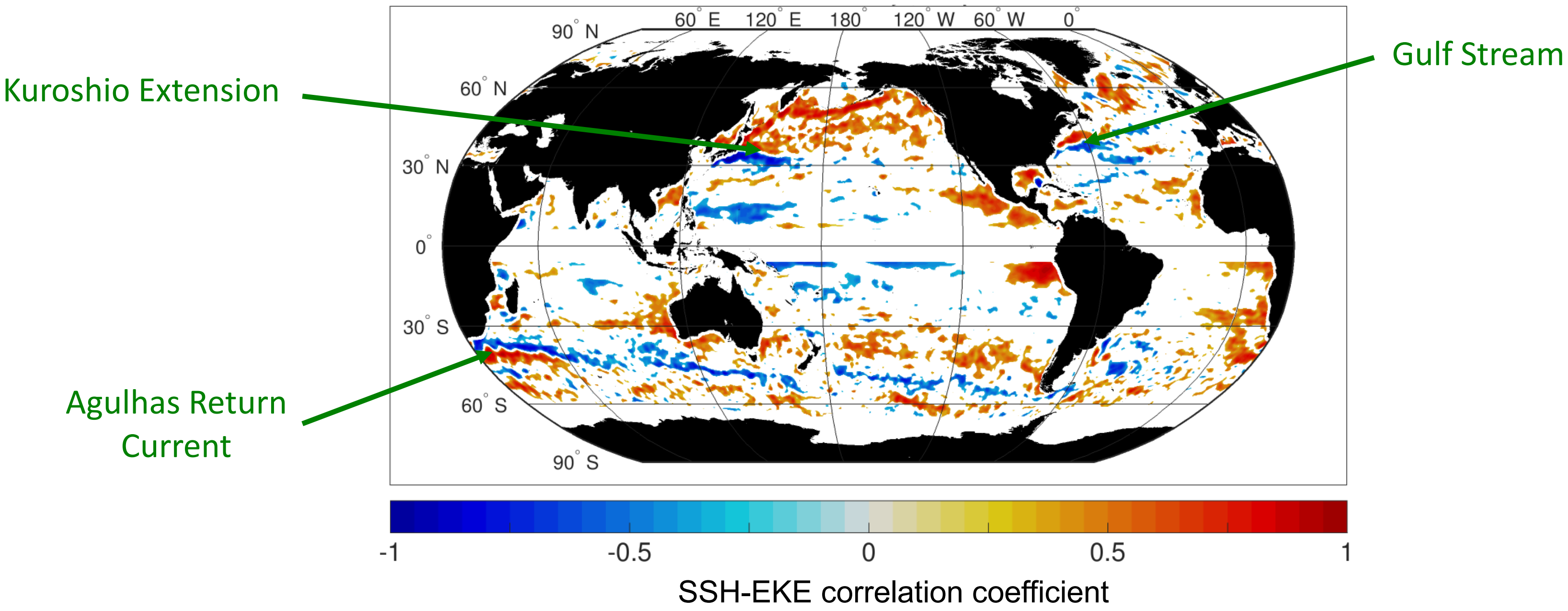


Wind stress curl forces PV anomaly



- Hence we have one mechanism for forcing of eddy activity in the west central SSIO
  - Downwelling (upwelling) wind stress curl enhances (inhibits) eddy activity by forcing PV anomalies

Global implications: the relationship between sea level and EKE



- The temporal variability of EKE is associated with sea level in a number of regions
- Some of these areas have energetic currents and very high levels of eddy activity

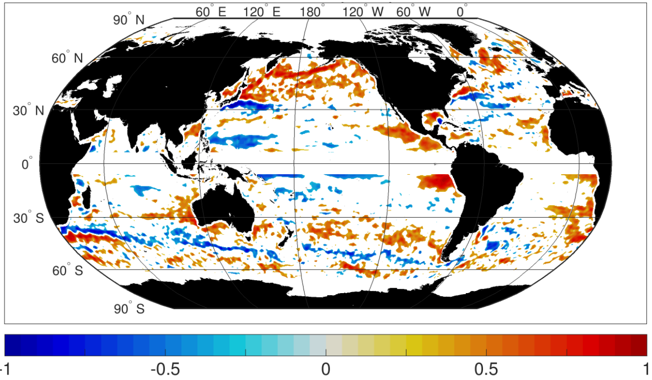
Global implications: the relationship between sea level and EKE

- The sea level-EKE relationship at interannual/decadal timescales may also have implications for multi-decadal trends

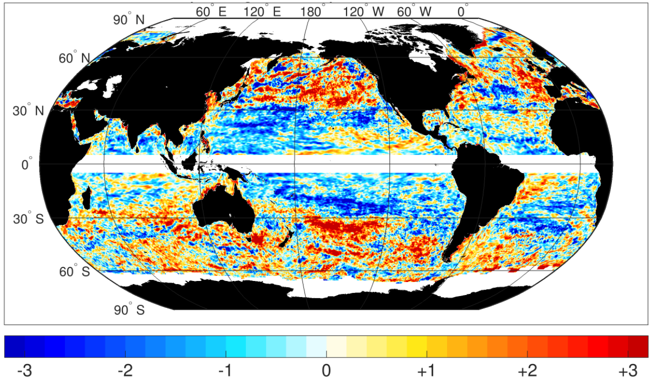
+ SSH-EKE corr. & + EKE trend → increased SSH trend?
N & S Pacific, S Indian

+ SSH-EKE corr. & - EKE trend → decreased SSH trend?
N Atlantic

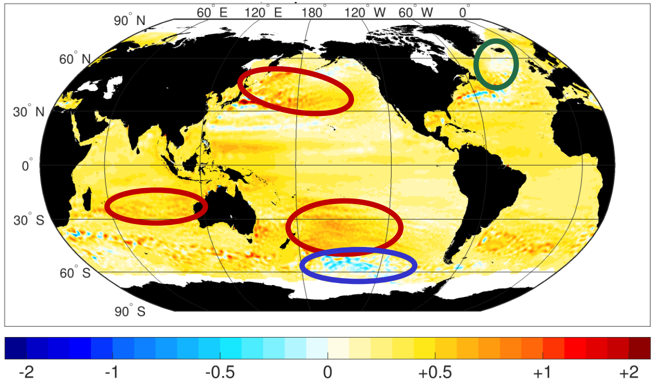
- SSH-EKE corr. & + EKE trend → decreased SSH trend?
S Pacific (just north of the Polar Front)



SSH-EKE correlation coefficient

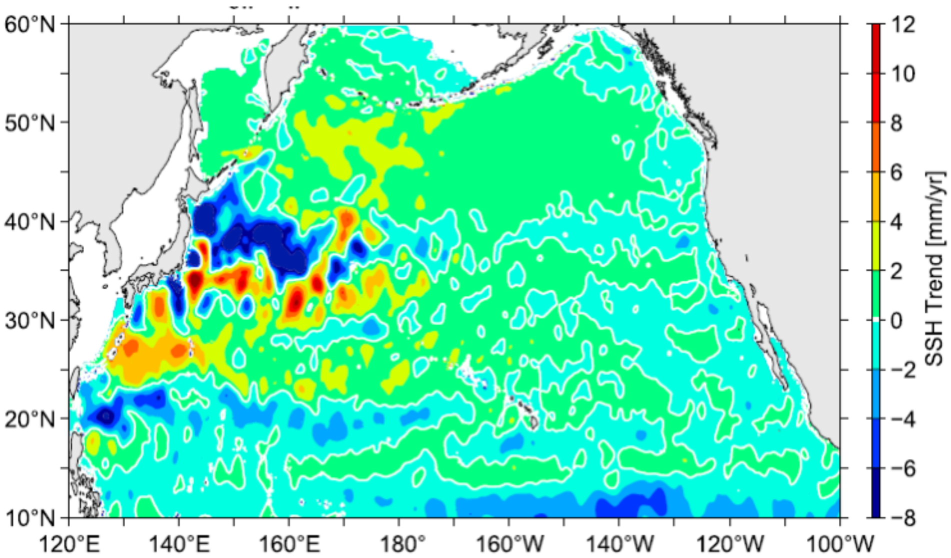


EKE trend (% yr^{-1}), 1993-2016



SSH trend (cm yr^{-1}), 1993-2016

Global implications: the relationship between sea level and EKE



Qiu et al. (2015)

Difference in sea level trend (1992-2013) forced by wind stress & eddy momentum fluxes, vs. wind stress alone

- Using a two-layer model, Qiu et al. (2015) found that eddy momentum fluxes can force multi-decadal sea level trends

Conclusions, and remaining questions

- ✓ Tropical Pacific sea level drives variations in mesoscale EKE in the eastern SSIO near Australia
    - ✓ Is responsible for the co-variability of sea level and EKE in this region

- ✓ Forcing from the Pacific is more robust on decadal than interannual timescales, and is likely driven by the Pacific Decadal Oscillation

- ✓ West of the Pacific-driven region in the interior SSIO, eddy activity is forced (at least in part) by variations in wind stress curl that change along-isopycnal PV gradients

- ✓ Mesoscale eddy activity may contribute to sea level variability and trends, by exhibiting a preference for anticyclonic or cyclonic eddies, or by forcing sea level changes through eddy momentum fluxes

For more info, keep an eye out for:

Delman, A. S., T. Lee, and B. Qiu, Interannual to multi-decadal forcing of mesoscale eddy kinetic energy in the subtropical southern Indian Ocean. *J. Geophys. Res. Oceans*, in review.

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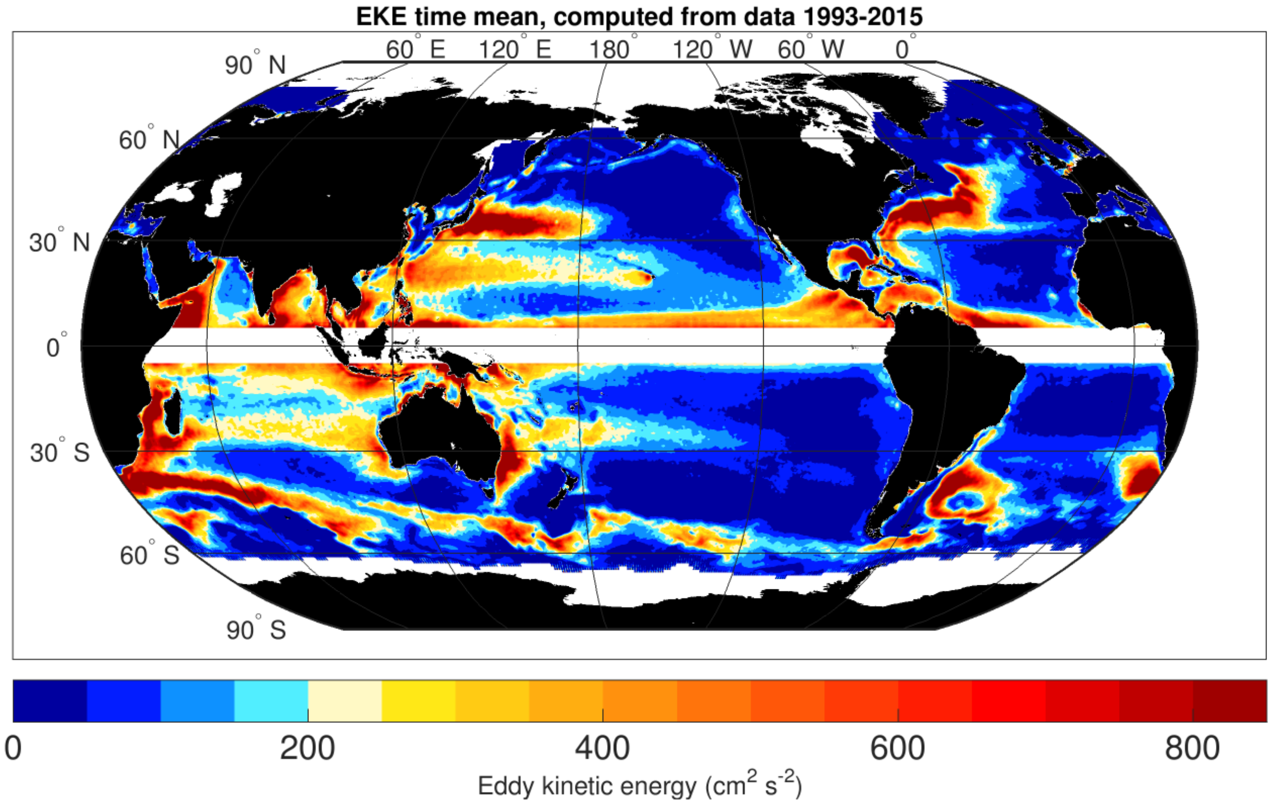
This research was supported in part by an appointment to the NASA Postdoctoral Program at the Jet Propulsion Laboratory, administered by Universities Space Research Association under contract with NASA.
The authors acknowledge AVISO+, CNES, and Copernicus for providing access to gridded dynamic topography and eddy trajectory data.

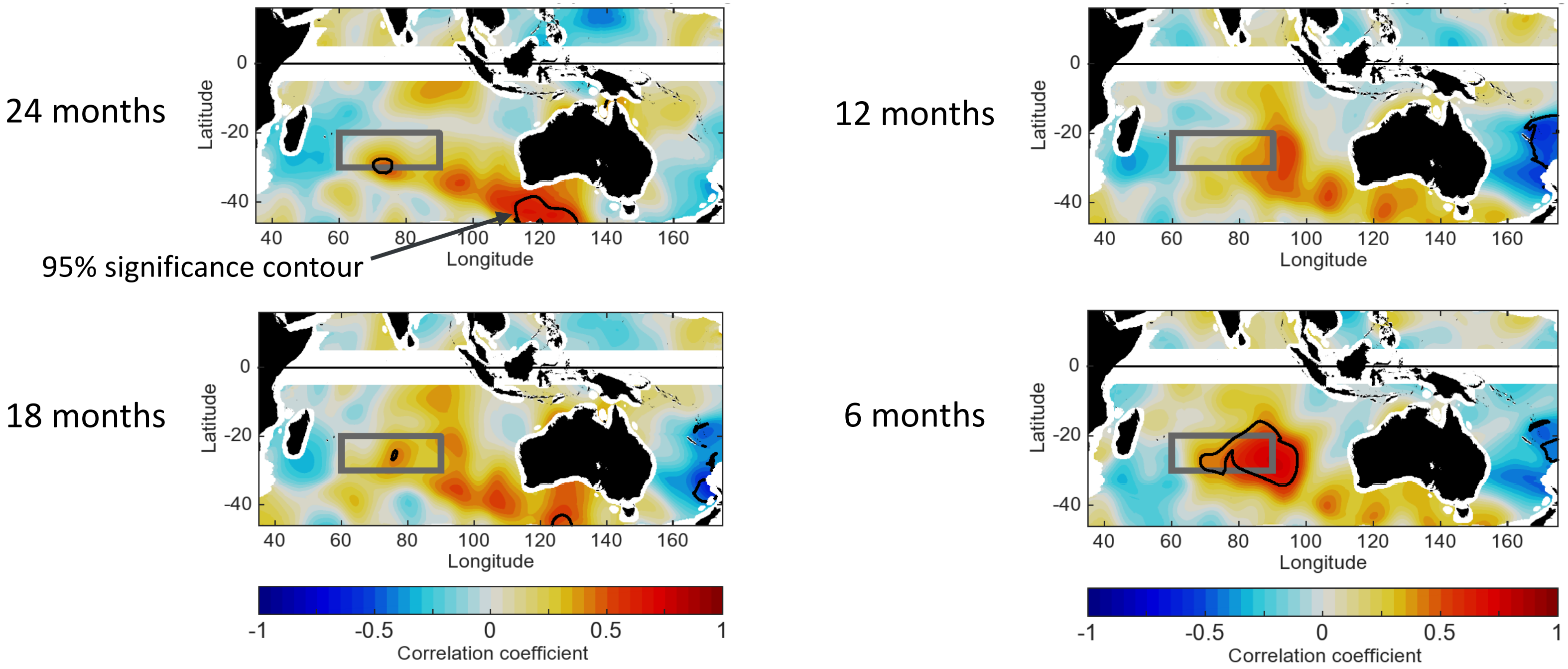
EKE time mean



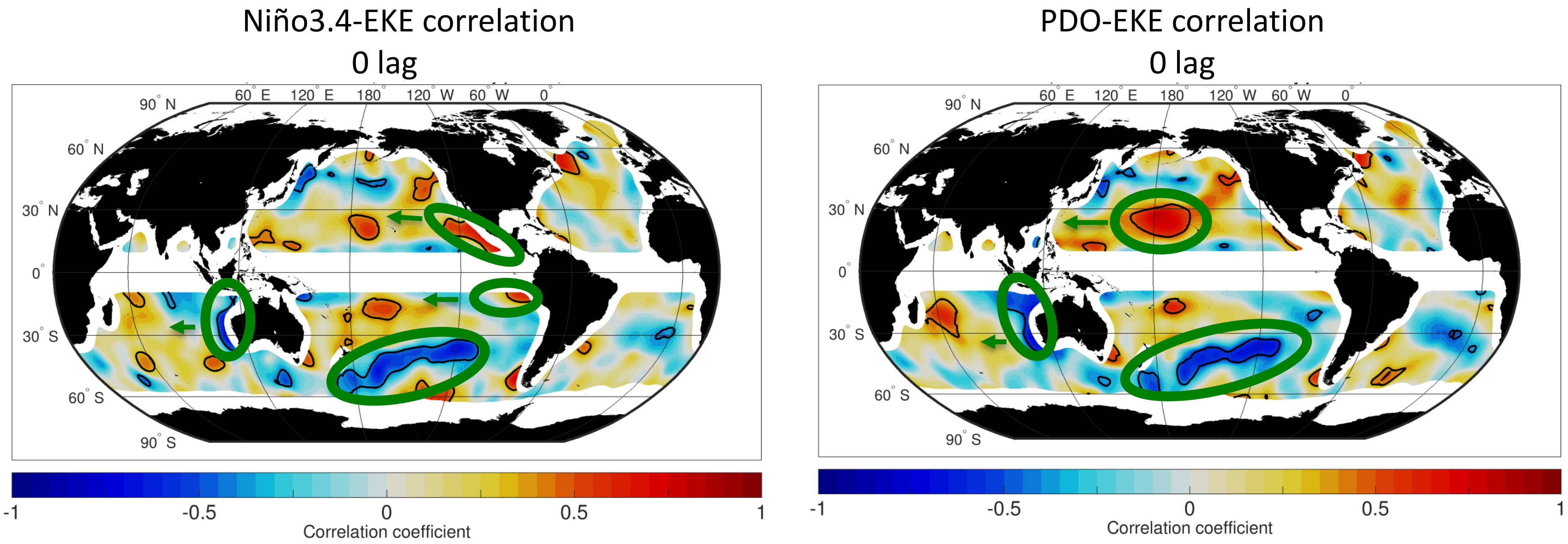
ID correlation of regional EKE_{meso} leading EKE_{meso} in the central/western SSIO

- Objective: look to see if temporal variability of mesoscale eddy energy propagates from another region, via an oceanic pathway

Leading box-averaged central/western SSIO EKE_{meso} by



Forcing of EKE interannual/decadal variability globally

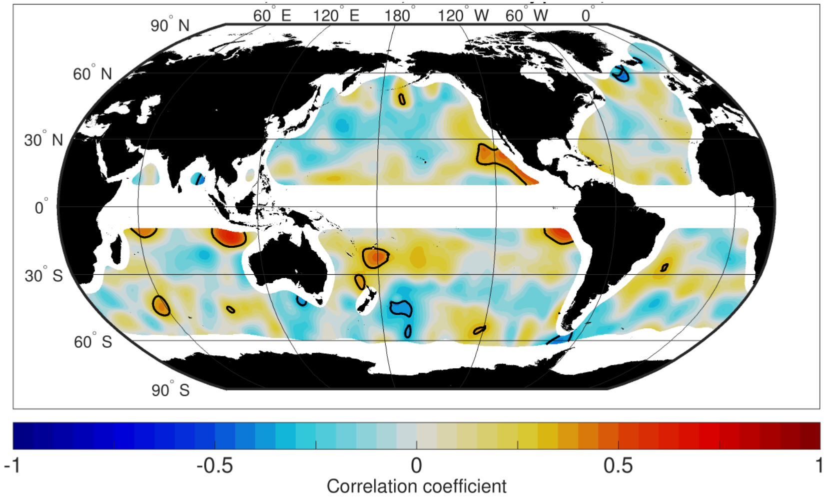


- Effect of the Pacific Decadal Oscillation (PDO) on EKE is similar to the effect of ENSO… but more focused on the interior of the ocean

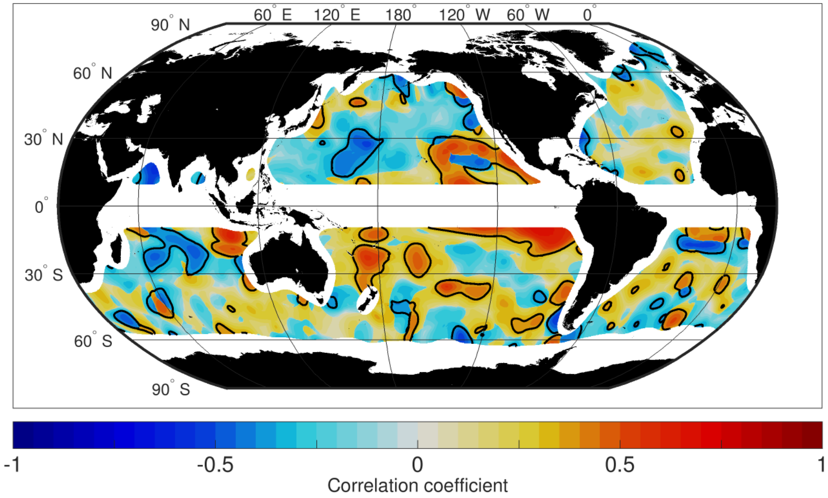
Forcing of EKE interannual variability globally

IOD-EKE interannual/decadal correlation

0 lag



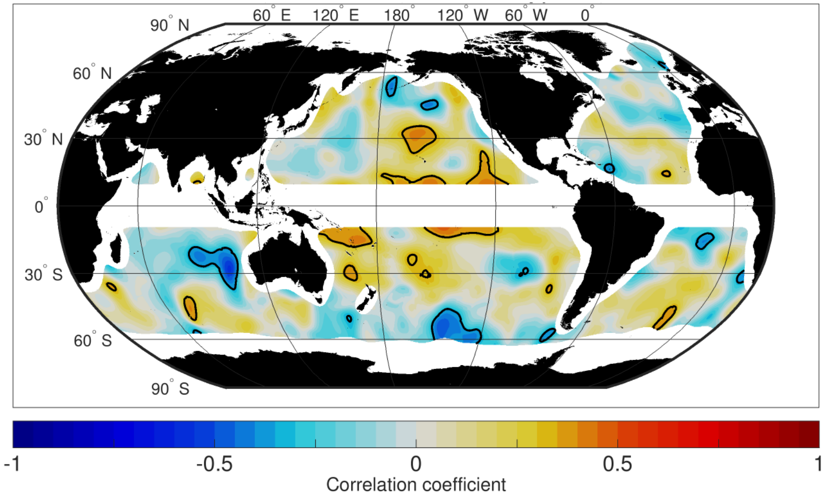
Optimum values: IOD leads EKE by 0-2 years



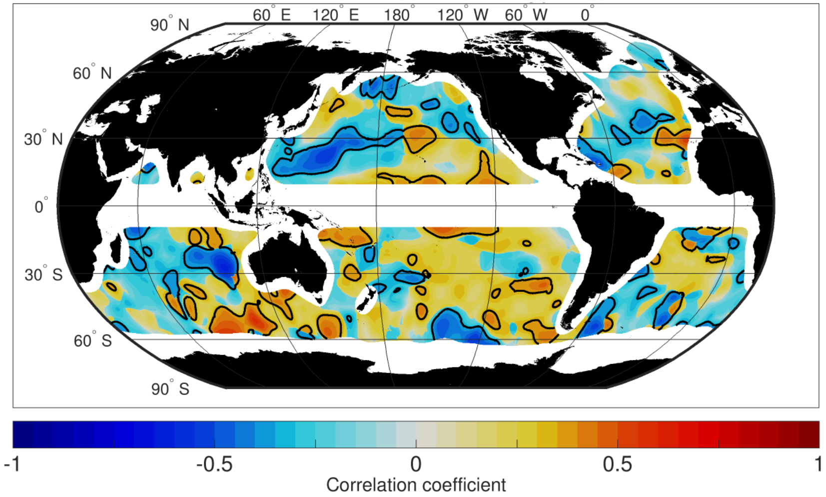
Forcing of EKE interannual variability globally

SAM-EKE interannual/decadal correlation

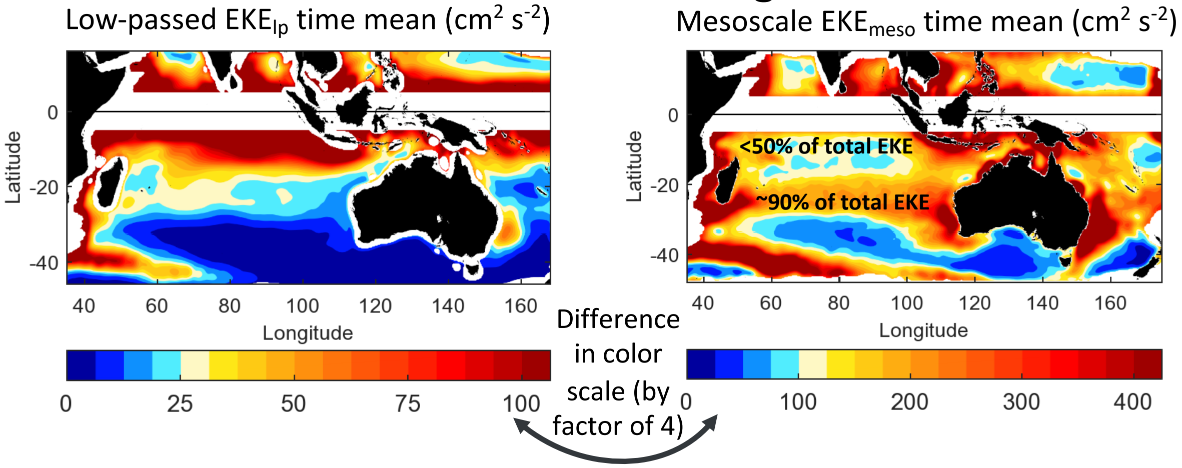
0 lag



Optimum values: SAM leads EKE by 0-2 years



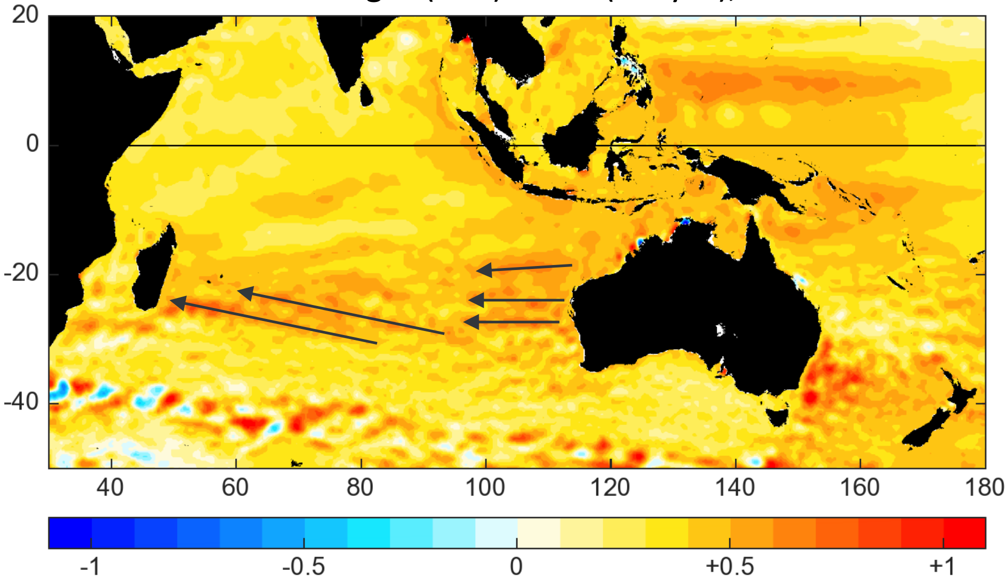
Distribution of EKE associated with large scales and mesoscales



Hypothesis 1: The interannual/decadal variability of EKE in the SSIO is driven by variations in the number of anticyclonic (warm-core) eddies
→ More AC eddies → EKE increases → SSH increases also

H H

Sea surface height (SSH) trend (cm yr^{-1}), 1993-2016

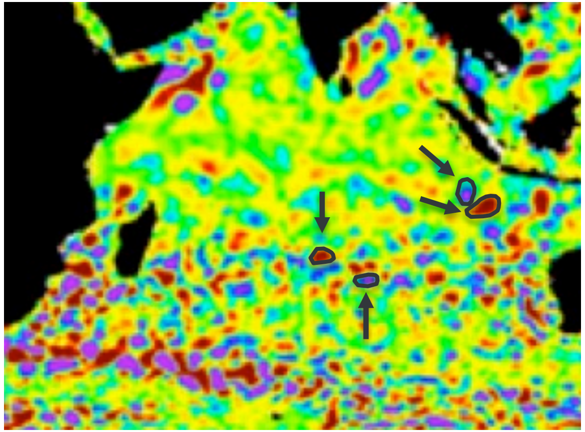


- Highly positive “tracks” in long-term SSH trend look like eddy propagation pathways

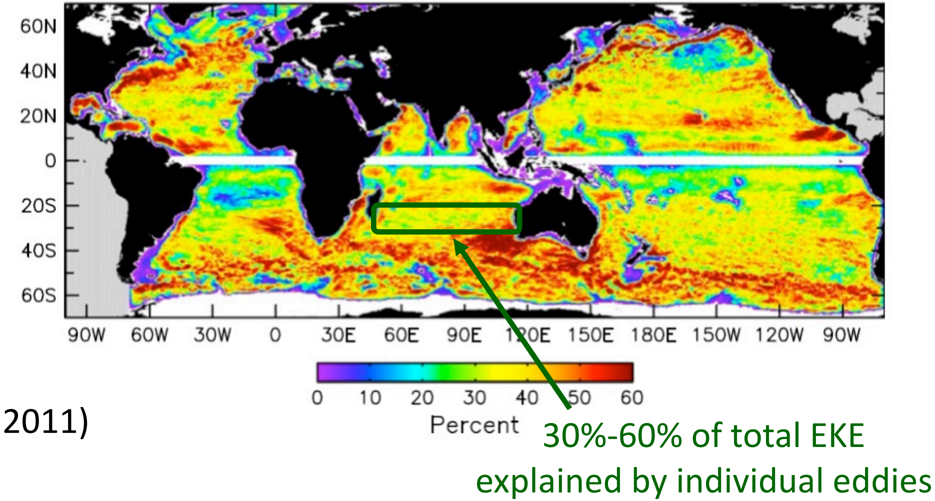
Mesoscale eddies and EKE – the eddy counting approach

- Isern-Fontanet et al. (2003; 2006), Morrow et al. (2004), and Chelton et al. (2007; 2011) have used algorithms to identify individual mesoscale eddies
- The Chelton et al. (2011) method identifies eddies as closed, compact contours of spatially high-passed sea level anomaly (SSH minus its time mean)

Spatially HP sea level anomaly, 28 Aug. 1996



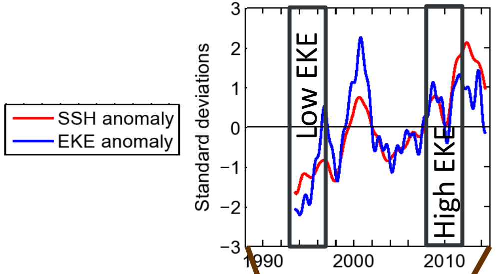
% of total EKE explained by mesoscale eddies (lifetime ≥4 weeks)



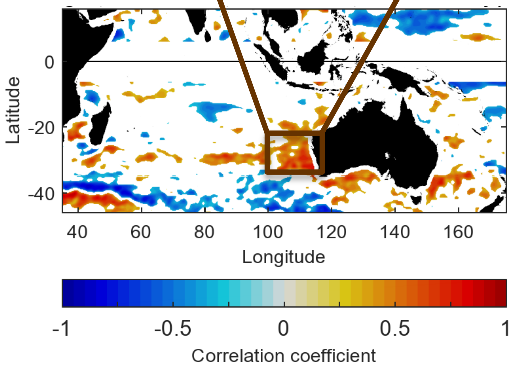
Chelton et al. (2011)

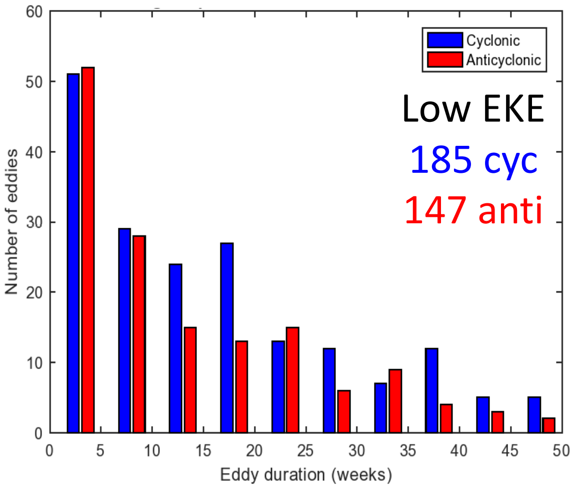
Do anticyclonic eddy variations explain SSH and EKE variability?

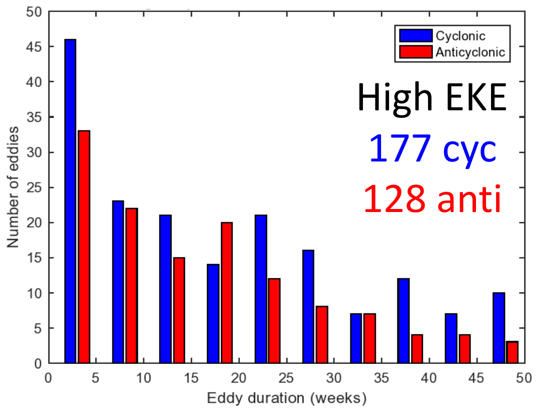
Histograms of cyclonic and anticyclonic eddies identified using the Chelton et al. (2011) method, during low and high EKE periods



SSH-EKE anomaly correlation (after detrending), 0 lag







~~Hypothesis 1:~~

~~More AC eddies → EKE increases → SSH increases also~~

- There are fewer anticyclonic than cyclonic eddies
- Number of AC eddies does not increase during high EKE & SSH periods